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Near-simultaneous plasma structuring in the midlatitude and equatorial ionosphere during magnetic superstorms

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[1] Near simultaneous formation of ionospheric plasma density structures at middle and equatorial latitudes during the intense magnetic storms of October 29–31, 2003, July 15, 2000, and March 30–31, 2001 is investigated. The evolution of these structures is explored by measuring amplitude scintillation of satellite signals at 250 MHz, determining zonal irregularity drifts and by detecting equatorial plasma bubbles with DMSP satellites. During abrupt decreases of SYM-H (1-minute resolution Dst) that signify the penetration of high latitude electric fields, an impulsive onset of scintillation occurs at Hanscom AFB (HAFB), a sub-auroral location, as well as in the equatorial region where the early evening period corresponds to the time of scintillation onset at midlatitudes. The onset of equatorial scintillation is delayed from that at midlatitudes by about 20 minutes which can be accounted for by considering instantaneous electric field penetration and plasma instability growth time of equatorial irregularities.

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1. Introduction

[2] During major magnetic storms the electric field imposed on the high latitude ionosphere almost instantaneously penetrates to middle and low latitudes on both the dayside and the nightside [*Abdu et al.*, 1991; *Fejer and Scherliess*, 1997; *Sastri et al.*, 2002] and is theoretically predicted to be damped on timescales of the order of tens of minutes due to an electrodynamic reaction of the magnetospheric plasma known as "shielding" [*Southwood*, 1977; *Richmond and Lu*, 2000]. Measurements of *Wygant et al.* [1998] on the CRRES satellite during the March 24, 1991 storm indicated that the large scale magnetospheric electric field penetrated into the inner magnetosphere between L = 2 and L = 4 when the rate of change of Dst was −50 nT/hr indicating fast ring current enhancement. The storm-time penetrating electric field can profoundly affect the distribution of plasma density in the ionosphere and can set-off or suppress plasma instabilities and create irregularities over a wide range of scale sizes ranging from tens of km to tens of m. Earlier work by *Aarons* [1991] showed the relationship between equatorial scintillation and the ring current during magnetic storms. More recently *Basu et al.* [2001a] found that when the rate of change of Dst exceeded −50 nT/hr during moderate storms, an abrupt onset of scintillation of 250 MHz signals from a geostationary satellite occurred at a midlatitude station with L = 2.8. The associated equatorial scintillation was observed in the longitude sector for which the early evening period corresponded to the time of rapid Dst variations and maximum Dst phase. In addition, during magnetic storms Joule heating at auroral latitudes causes a change in the global circulation pattern in the thermosphere and the ionosphere to give rise to an ionospheric disturbance dynamo [*Blanc and Richmond*, 1980; *Fuller-Rowell et al.*, 2002; *Fejer and Emmert*, 2003]. The changes in the plasma density distribution and the formation of plasma density irregularities in the ionosphere during magnetic storms affect the propagation of transionospheric radio signals and can severely impact satellite communication and navigation systems.

[3] The formation of plasma density irregularities causing scintillation of satellite signals at midlatitudes and the equatorial region is investigated for the Halloween storm of October 29–31, 2003. This storm period is marked by three rapid ring current injections causing the rate of change of Dst to exceed −50 nT/hr. These changes indicating magnetospheric electric field penetration into the plasmasphere are examined in the context of the generation of plasma density irregularities causing onsets of scintillation of satellite signals at middle and equatorial latitudes. It is shown that the irregularity onsets followed a similar pattern during the major magnetic storms of July 15, 2000 and March 31, 2001. In addition, during these complex storms, the Joule heating in the auroral region, as indicated by the enhancement of the auroral electrojet (AE) index, may set up an equatorward neutral wind system. This often sets-off the ionospheric disturbance dynamo several hours prior to the prompt penetration of high latitude electric field, as for example in the case of July 15, 2000, when the storm enhanced AE index exceeding 1000 nT occurred over a 12 hour period prior to the minimum SYM-H value of −295 nT at 2200 UT.

[4] In this paper we investigate the manner in which the plasma structuring and plasma dynamics in the midlatitude and the equatorial ionosphere were affected during these intense storms when the prompt penetration of the electric field occurred in the presence of disturbance dynamo effects.

2. Observations

[5] The effects of intense magnetic storms of October 29–31, 2003, July 15–16, 2000 and March 30–31, 2001 on

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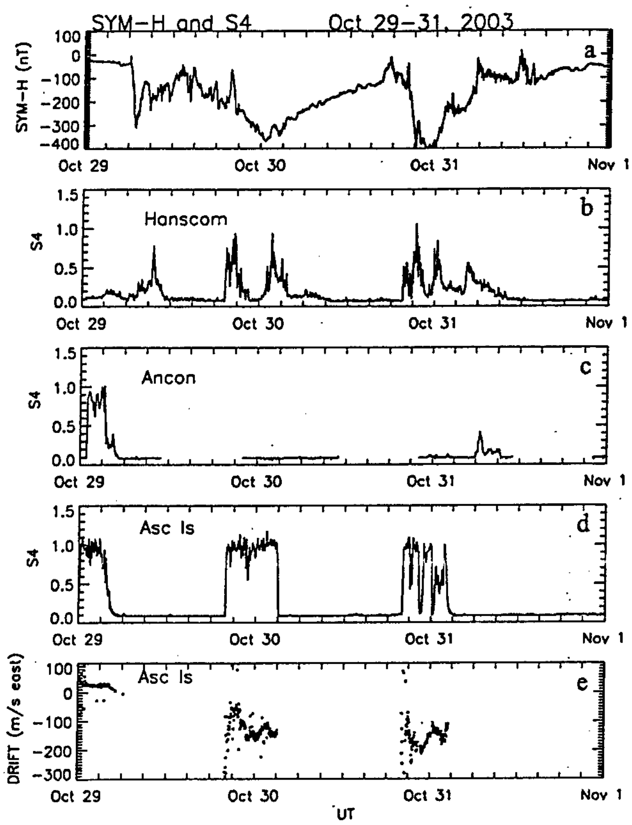

Figure 1. Scintillations at 250 MHz from geostationary satellites recorded at Hanscom AFB, MA, Ancon, Peru and Ascension Island together with its irregularity drift plotted against SYM-H for Oct 29–31, 2003.

the midlatitude and equatorial ionosphere were studied from both ground and space based measurements. The ground segment at midlatitudes comprised of 250 MHz scintillation measurements at HAFB (350-km ionospheric intersection at 39° N, 74.7°W, 53° invariant) by using transmissions from a geostationary satellite. In the equatorial region, 250 MHz satellite scintillation measurements by the Air Force Research Laboratory's (AFRL) network of stations at Ancon, Peru, (12°S, 74.7°W; diplat 1.0°N) on the magnetic equator and at Ascension Island (7.9°S, 14.4°W; diplat 16.°S) near the southern crest of the equatorial anomaly were used. At Ascension Island the spaced receiver scintillation measurements provided the zonal drift of plasma density irregularities and this result was used to determine the effects of the ionospheric disturbance dynamo on the zonal plasma drift in the equatorial region.

[6] The continuous scintillation measurements made by the AFRL scintillation network were useful for tracking the onset of scintillation at middle and equatorial latitudes and determining its relationship to electric field penetration during ring current enhancements and fast decreases in SYM-H. In the absence of stations at particular longitudes, the ground segment was supplemented by the ion density data from the sun-synchronous polar orbiting DMSP satellites (at 840 km with an inclination of 97.8°) to determine the presence of equatorial plasma bubbles [*Basu et al.*, 2001b].

3. Results and Discussions

[7] Figure 1a shows the variation of SYM-H during the storm period of October 29–31, 2003 and Figure 1b shows the scintillation index S4 at 250 MHz recorded at HAFB from a geostationary satellite. The first impulsive onset of scintillation occurred at 0730 UT with a maximum value at 0940 UT in concert with a sharp decrease of SYM-H after 0700 UT that corresponds to a rate of change of Dst of −90 nT/hr. The other two scintillation onsets shown in Figure 1b at 1930 UT on October 29 and 1935 UT on October 30 occurred during sharp decreases in SYM-H. Thus the impulsive onsets of irregularity generation at sub-km scales, that cause 250 MHz scintillation, were observed at HAFB during rapid decreases of SYM-H signifying the penetration of high latitude electric fields. However, at this time the auroral oval also expanded equatorward and engulfed this sub-auroral station at L = 2.8 and hence the impulsive onset of scintillation at HAFB is attributed to auroral irregularities [*Basu et al.*, 2005].

[8] Figure 1c shows that Ancon located near the magnetic equator at 75°W did not observe any scintillation at the 350-km intersection point of 10.9°S, 78.7°W during the

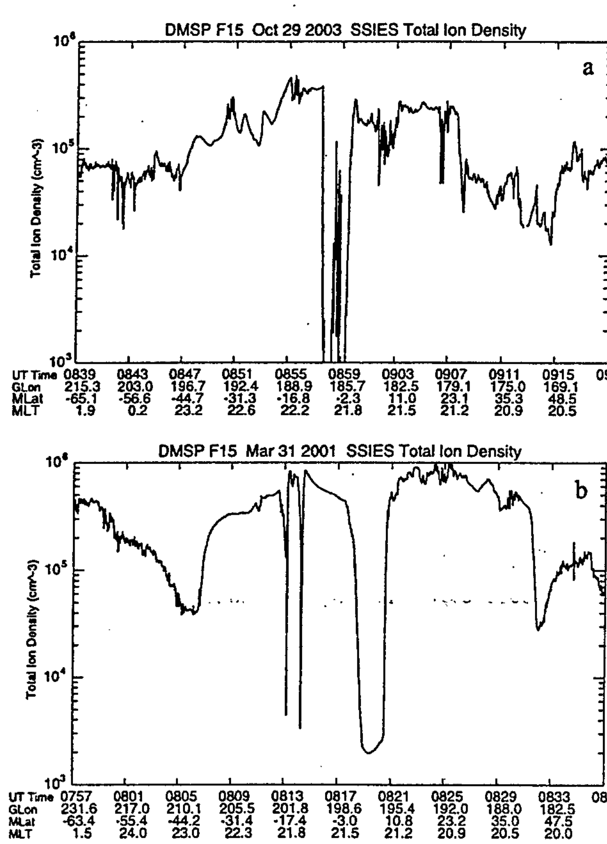

Figure 2. (a) Total in situ ion density recorded by the DMSP F-15 satellite on October 29, 2003. A plasma bubble was detected at 0859 UT at 186 E longitude. (b) Same as (a) but on March 31, 2001, indicating presence of a plasma bubble at about 0820 UT at 195 E longitude.

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14. ABSTRACT
Near simultaneous formation of ionospheric plasma density structures at middle and equatorial latitudes during the intense magnetic storms of October 29—31, 2003,, July 15, 2000, and March 301-31, 2001 is investigated. The evolution of these structures is explored by measuring amplitude scintillation of satellite signals at 250 MHz, determining zonal irregularity drifts and by detection equatorial plasma bubbles with DMSP satellites. During abrupt decreases of SYM-H (1-minute resolution Dst) that signify the penetration of high latitude electric fields, an impulsive onset of scintillation occurs at Hanscom AFB (HAFB), a sub-auroral location, as well as in the equatorial region where the early evening period corresponds to the time of scintillation onset at midlatitudes. The onset of equatorial scintillation is delayed from that at midlatitudes by about 20 minutes, which can be accounted for by considering instantaneous electric field penetration and plasma instability growth time of equatorial instabilities

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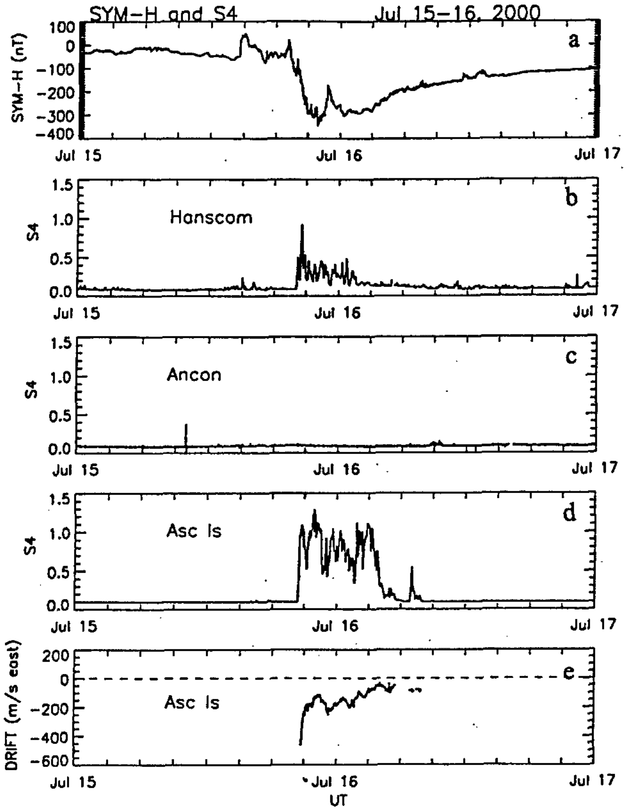

Figure 3. Same as Figure 1 but for July 15–16, 2000.

entire storm period. We attribute the absence of scintillation at Ancon to the fact that the electric field penetration and the corresponding midlatitude scintillation onsets (Figure 1b) at 1930 UT on October 29 and at 1935 UT on October 30 did not correspond to the time of local sunset at Ancon. The longitudinal conductivity gradient in the ionosphere at the time of sunset is a prerequisite for the generation of equatorial irregularities. However, at Ascension Island (7.9°S, 14.4 °W) located in a different longitude sector, these times did correspond to the local sunset period and Figure 1d shows that scintillations were indeed observed on both occasions at 1955 UT on October 29 and 2000 UT on October 30, respectively. Thus the onsets of the equatorial scintillation at Ascension Island were delayed from that at HAFB by about 25 minutes. We consider that the electric field instantaneously penetrated from high latitudes to the equatorial region. The observed delay of scintillation onset at Ascension Island corresponds quite well with the tens of minutes growth time of equatorial irregularities by the Rayleigh-Taylor instability mechanism [*Ossakow*, 1981]. It should be noted from Figure 1 that under magnetically quiet conditions at the beginning of October 29, 2003, both Ancon and Ascension Island recorded scintillations, as is to be expected [*Basu et al.*, 2002] but scintillations were suppressed at Ancon during the storm indicating the development of well-defined longitudinal boundaries of scintillation during magnetic storms. Based on the above consideration, we expect that the first scintillation event at 0730 UT on October 29 shown in Figure 1b should be associated with plasma structures in the equatorial ionosphere at a location approximately 12 hours apart where the local time would be 1930h, which would be in the 180°E longitude sector. In the absence of any scintillation station in this longitude sector, we illustrate in Figure 2a the ion density data obtained by the DMSP F15 satellite at 840 km that shows, as expected, a deep ion density depletion at the equatorial crossing of 186°E. The ion density depletion indicates the generation of plasma bubbles by the Rayleigh-Taylor instability mechanism, which is presumably initiated by the storm-time penetration electric field. The satellite did not however detect irregularities in other longitude sectors on this day.

[9] Returning to Figure 1e, we find the results of the spaced receiver scintillation measurements made at Ascension Island. It is interesting to see that before the onset of the storm, the zonal irregularity drift at Ascension was 30ms^{-1} eastward around local midnight but several hours later during the onset of scintillations at dusk that evening the measured zonal drift was 150 m s^{-1} westward during October 29–30 and then became as large as 200 m s^{-1} westward during October 30–31. The storm-time Joule heating at auroral latitudes causes an equatorward neutral wind that turns westward under the action of the Coriolis force [*Richmond and Lu*, 2000]. The westward irregularity drift results from this westward neutral wind. It is interesting to note that equatorial irregularities can be formed at the time of sunset even when the disturbance dynamo conditions prevail [*Blanc and Richmond*, 1980; *Fejer and Scherliess*, 1997].

[10] We discuss two other intense magnetic storms that showed similar ionospheric response in the midlatitude and the equatorial region. First we consider the July 15–16, 2000 storm shown in Figure 3. Figure 3b shows, that as in the case of the Halloween storm, the onset of 250 MHz scintillation at HAFB occurs at 2010 UT during a sharp decrease of SYM-H starting at 2000 UT (Figure 3a), associated with rapid ring current enhancement and penetration of west to east electric field during daytime. This onset time corresponded to the post-sunset period in the

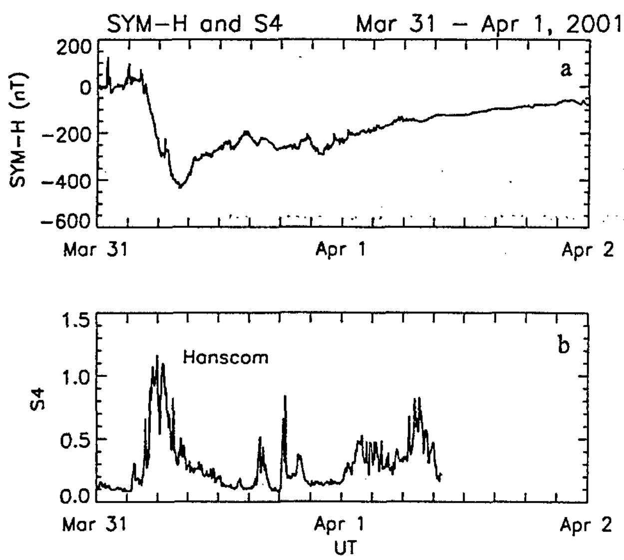

Figure 4. Same as Figure 1 with only Hanscom scintillation data for March 31–April 1, 2001.

equatorial region at Ascension Island (14.4°W) and Figure 3c shows that the scintillation onset was indeed recorded there 15 minutes after the onset at HAFB. This delay is probably caused by the plasma instability growth time for equatorial irregularities as mentioned earlier. Figure 3e also shows that the irregularity drift was westward at the time of the onset of equatorial scintillation.

[11] Figure 4 shows (a) the variation of SYM-H during the March 31, 2001 storm and (b) the S4 index of 250 MHz scintillation recorded at HAFB. Two scintillation events occurred on March 31. The first event commenced at about 0500 UT during the main phase of the storm between 0400 UT and 0812 UT that encompassed the local midnight period. For the first event at about 0500 UT, the equatorial irregularities are expected at a longitude of about 225°E where at this time the post-sunset period of 2000 LT will prevail. Figure 2b shows that indeed as expected the DMSP F-15 satellite detected a deep plasma density depletion at 840 km around the magnetic equator at 197°E. On this day no bubbles were detected by the DMSP satellite at other longitudes. The second scintillation event at HAFB is comprised of three short bursts of scintillation, at about 1800 UT when SYM-H decreased during the recovery phase of the storm. *Foster et al.* [2002] have shown that during this local afternoon event a westward convecting plume of much enhanced total electron content (TEC) formed at middle latitudes and extended from the southeast to the northwest.

[12] It is significant to note that no irregularities were detected by Ancon at 79°W longitude sector during these three intense magnetic storms. The electric field penetration occurred at a time that did not correspond to the sunset period in this sector that provides steep longitudinal gradient in the ionospheric conductivity necessary for the irregularity generation. As such, models based only on observations at one particular longitude may not account for the global response of the equatorial ionosphere. Further, it is interesting to note that the onset of equatorial irregularities during the post-sunset period could occur when the disturbance dynamo conditions prevailed, contrary to model predictions [*Fejer and Scherliess*, 1997]. The Halloween storms have provided us with a unique opportunity to study the ionospheric plasma structuring and dynamics during distinct electric field penetration events. We hope that the results presented in the paper on the ionospheric response to the main phase of magnetic storms will provide the essential input to coupled ionosphere-magnetosphere models currently undergoing development.

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